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# UNDER WHAT CIRCUMSTANCES CAN FOREST BELTS REDUCE THE CONCENTRATION OF WASTE GASES

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[In welchem Fall können Waldstreifen die Rauchgaskonzentration vermindern?]

Luft- und Kältetechnik, 6, 1967, pp. 255-258.

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# UNDER WHAT CIRCUMSTANCES CAN FOREST BELTS REDUCE THE CONCENTRATION OF WASTE GASES?[1]

Four effects have to be differentiated in the action of forest belts and forest fringes on the distribution of waste gases and smoke damage: reduced wind velocity; increased turbulence which remains active even beyond the leeward fringe of a forest; the actual filtering by the plants, which is usually minor; and the physiological relief of the plants as a result of a wind screen. The concentration of smoke gases can be reduced by forest belts only in very rare cases, i.e. when it decreases markedly with increasing height above the ground, e.g. at sites which are above the original level of smoke distribution. The fourth effect (protection from wind) is of major practical importance.

The main factors which influence and determine the diffusion of smoke are wind and turbulence. Turbulence means the irregular movement in addition to mean wind velocity, gustiness, mixture of air, and exchange of air between various layers of air. To understand the effects of a forest on the diffusion of smoke, it is necessary to consider first of all the influence of the forest on wind and turbulence. Then it is necessary to clarify the influence of the conditions of wind and turbulence in their changed form found in forests on the diffusion of smoke. We must differentiate here between solid immissions (dust) and gaseous immissions (e.g. $SO_2$), because wind and turbulence have different effects on these two types of immission.

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1. 67th Report of the Working Group "Research on Forestry Damage from Smoke," Tharandt.

Doubtlessly, there are especially favorable conditions for sedimenting the solid immissions in the interior of forests as a consequence of reduced wind velocity and turbulence. The dust content of the air is reduced in the forest because the dust adheres to the plants or parts of plants. This effect extends even in the leeward direction of the forest.

The present paper will discuss gaseous immissions in more detail. However, it will not present any measurement results but rather offer theoretical meteorological models. This is not to say that we deny the importance of measurements or would want to belittle their validity. But without theoretical models it is hardly possible to interpret measurements in their true perspective. Both methods of study can and should compliment, and stimulate each other. This paper will extend and define some earlier studies [1, 2].

Forest fringes are of decisive importance with respect to the effects of forests on the distribution of smoke. This is to be understood as referring to the fringes of entire forests, i.e. not to any borders between two forest stands which differ little from, and are immediately adjacent to each other, or to the edges of opening sides, glades and felling areas. The open area has to be covered by wind currents over an area of at least 400 to 600 meters before the wind hits against the edge of the forest. This type of forest border represents a rise in terrain on the one hand, and an area of increasing or increased roughness, on the other hand. A meadow or field is considerably more level than the surface of a forest, even if it is homogeneous. For large-scale topographical considerations, the effect of terrain graduation is less noticeable. But the forest as a whole acts as an area of increased roughness, not only because of its

roof formed by tree tops. The following study will primarily discuss forest belts which are not too wide because the conditions there can be more easily surveyed.

Wind velocity markedly decreases in the area of a forest belt and forest stands, to about 10 to 20% of the value in the open field, if expressed in mathematical terms. The reduced wind velocity corresponds at the same time to an increased cross section of the flow if the same volume of air is considered. For example, if water flows through a pipe having a varying diameter, a high flow rate corresponds to a large diameter. Air flowing through the tree trunk area has a smaller vertical depth before it enters the forest stand or forest belt as a result of its greater velocity. Thus, the air flowing through the tree trunk area is the particular volume of air which forms the layer that is closest to the ground in the open field. The streamlines along which the air particles are moving are fanned upwards at the windward edge of the forest. The flow of air "lifts off the ground." This is illustrated, for example, by Baumgartner [3]. Wind velocity is still relatively low immediately above the tree tops as a result of the braking action of the rough crown cover. Wind velocity gradually increases as the altitude increases. It becomes slightly faster than wind velocity in the open field if the forest belt is not too wide, until it finally returns to the undisturbed velocity of the open field at a considerable altitude above the forest. This intensification of wind in a small area is most marked above the first row of trees of small forest belts, while it is lacking above wide forest areas. The influences of the windward edge of the forest are counterbalanced in the area of the leeward edge of the forest; the

flow returns more and more to its original form. This readaptation takes place much more slowly than the upward fanning of the streamlines at the windward edge of the forest. These effects of the forest on wind velocity extend to a distance of about 5 to 10 times the height of the stands from the forest fringe on the windward side, and to as much as 20 to 30 times the height of the stands from the forest fringe on the leeward side [4].

In absolute terms, turbulence is reduced in the area of forest stands and forest belts in a manner similar to that of wind velocity. The situation is different for relative turbulence, i.e. the turbulence relating to wind velocity (quotient of turbulence/wind velocity). Due to the barrier action of the forest, the vertical component of relative turbulence is particularly increased. The two factors contributing to this effect are firstly, the roughness of the crown cover, and secondly, the change in direction of flow at the windward edge of the forest. In the area of wind intensification in a limited area (especially on the windward edge) of small forest belts, the absolute turbulence is even higher than in the open field. The windward edge of the forest is of great importance for the turbulence. If the effect is considered on a larger scale, the effect of changing the wind direction at a graduation in terrain at the windward edge of the forest becomes transformed into the effect of increased roughness of the forest belt on the whole.

In the assessment of the influence of wind and turbulence on the diffusion of smoke it must be considered that the interdependence of waste gas concentration on altitude can be represented by a Gaussian distribution (bell-shaped curve) according to the theory of the diffusion of smoke. The axis of the trail of

smoke lies in the apex of the normal distribution, and concentration gradually falls off above and below the apex. In flat regions, the axis of the smoke streamer usually is above the forest when high smoke stacks are present. Therefore, the concentration of smoke increases with increasing altitude above the ground until the axis of the trail of smoke is reached. A decrease in concentration with increasing altitude occurs for sources of smoke at the level of the earth's surface, for example in open-pit mines. In addition, the concentration decreases as the altitude increases, if the site of the forest is on an elevation (forests located on mountain peaks or slopes) which raise the forest above the original level of the axis of the smoke streamer. In the area of industrial centers with numerous smoke sources of varying heights, the concentration of the waste gases may be approximately constant at various altitudes. The axis of the smoke streamers are not at the level where the smoke stacks end, but are mostly higher up at the so-called effective smoke stack height as a result of a thermic lift and the radiating flow property of waste gases. This effective height can be mathematically computed from technical and meteorological parameters.

What effect does wind velocity have? The original normal distribution is distorted between the two edges of the forest because the streamlines fan out at the windward side and approach each other again at the leeward side. Therefore, those concentrations predominate in the interior of a forest belt or forest stand which were present in the open field in the layer of air closest to the ground across which the air passed prior to reaching the forest. Beyond the leeward fringe of the forest, conditions again approach those that were prevalent in front of the windward fringe of the forest.

What is the effect of turbulence? The increased (vertical) turbulence tends to flatten and widen the altitude profile of the normal distribution of waste gas concentration. It is most pronounced at the windward edge of the forest with its stong increase in relative and partly absolute turbulence. The maximum value at the axis of the plume of smoke falls off, while the concentration increases at the lateral extensions of the normal distribution. The area below the normal curve and/or the volume of waste gas gathered above all altitude layers remains constant here, if there are no other forces which lead to its decrease. One of these forces is, for example, the continuous turbulence of waste gases, which moves also in a transverse direction to the plume of smoke. Another force is the gradual chemical decomposition of waste gases, which might occur. But these effects are of minor importance in this context.

An essential difference between turbulence and wind velocity is found in the fact that the changes caused by the windward edge of a forest are not balanced out and eliminated by the leeward edge of a forest. Turbulence is a process which decreases order and increases disorder. The distribution of waste gases which becomes flatter and wider as the turbulence increases means an increase in "disorder" or "randomness" of the altitude profile. A measure for the disorder or random development of the distribution is entropy. But we do not want to discuss this in more detail. According to the 2nd law of thermodynamics (the principle of entropy), entropy can never decrease without any external influences, i.e. the disorder or random development of a system can only increase. Flattening and widening of the original normal distribution is not balanced out again on the other side of the leeward fringe of the forest.

The situation is the same as when red and white small spheres of the same kind are mixed in a container. The spheres can be mixed by simply shaking the container, i.e. the disorder or chance distribution can be increased. But even after extended shaking, the spheres cannot be sorted according to their color, i.e. their order cannot be increased. Without any external intervention, entropy can merely increase. The turbulence in the distribution of smoke corresponds to shaking the spheres in the example given above. In solid dust particles, the earth's gravity provides the necessary intervention to increase order. Therefore, the dust is able to settle to the ground.

In all these considerations, it is necessary to differentiate clearly between short-term (instantaneous) and long-term (stationary) processes. This will be demonstrated by an example. Let us imagine a gutter with a turbulent flow. The speed at the surface is to be greater than at the bottom, turbulence is to cause the constant mixing of the layers of water. A small amount of dye is now added once to the bottom of the gutter. The dye is immediately moved to the upper layers of water by turbulence. Then the concentration of dye is established at one measuring point, slightly below the point where dye is added to the flow. The dye concentration will be greater on the surface than on the bottom because the upper layers of water precede the lower layers. This corresponds to a short-term process. However, if dye is added for a long period, the high content of dye in the lower layers of water will also reach the measuring point. And because turbulence has not yet completely balanced the distribution as far as the measuring point, the dye concentration will now be greater on the bottom than at the surface. Thus, the findings are exactly the opposite for the short-term and long-term example.

In practice, the long-term processes are naturally decisive. Incorrect conclusions may be drawn from short-term observations, for example in tests with artificial smoke clouds or in measurements of gas concentrations in forests. These conclusions may not only be erroneous with regard to their quantitative findings but they may possibly be completely wrong in principle and, therefore, useless. Therefore, findings of short-term measurements must not be applied to long-term processes in practice without critical evaluation.

By means of the tools obtained, the interrelation between forest belts and distribution of smoke and/or smoke protection may be represented in a summarizing manner. Of the total of four effects, the first two are of a purely meteorological nature, the latter two are largely also of a physiological nature.

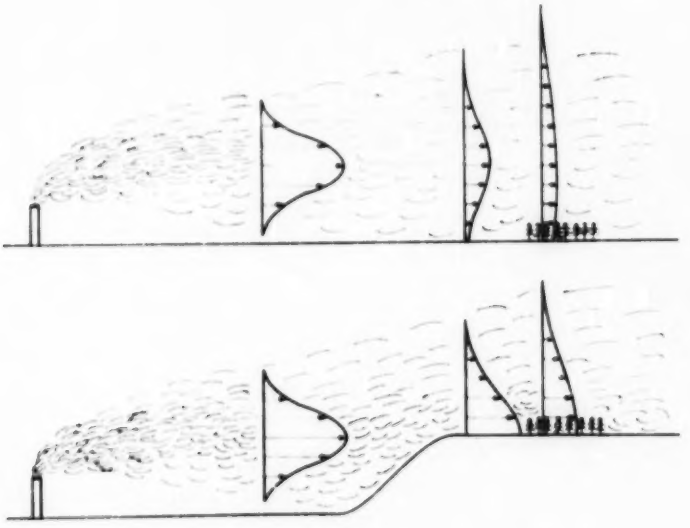

Figure 1. Schematic of the influence of turbulence on the concentration of waste gases in the forest belt areas. (explanations in the text).

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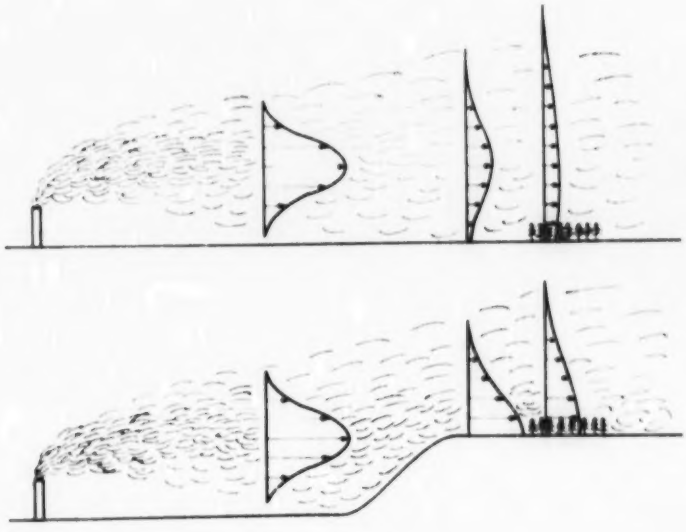

Figure 1. Schematic of the influence of turbulence on the concentration of waste gases in the forest belt areas. (explanations in the text).

The Wind Influence Excluding Any Consideration of Turbulence

The streamlines fan out in the tree trunk area, the flow as a whole is lifted off the ground. In the trunk area there are concentrations in a stationary case as they occur in the layer closest to the ground in the area in front of the forest belt. For an original concentration increase with increase in height (flat land), concentration will slightly drop in the trunk area, whereas for an original decrease with increase in height (locations above initial fanning level of the axis of the smoke streamer) it will slightly rise. The changes caused by the windward edge of the forest are canceled again to an great degree in the area on the other side of the leeward edge of the forest, even though this is accomplished only at a relatively great distance from the forest.

The Influence of Turbulence (Figure 1)

Increased turbulence of the forest belt as a whole, especially of the windward edge of the forest, increases the turbulent action of waste gas. If the concentration increases as the altitude increases (flat lowland), the corresponding normal curve of distribution becomes flattened. When the total volume of smoke remains constant, concentration has to increase somewhat on the ground, i.e. additional smoke is whirled from the top to the bottom. When the concentration decreases as the altitude increases (forests located above the original level of distribution of the axis of the plume of smoke, e.g. slopes higher up on mountains, and mountain ridges), the earth surface lies in the apex of the normal distribution, and the increased turbulence causes the concentration to become lower close to the ground. The smoke is whirled upwards. The effect of the windward edge is not balanced out again on the leeward edge

of the forest (2nd law of thermodynamics).

The Actual Filtering of Waste Gases

Even though waste gases accumulate on plants and plant parts in connection with physiological processes, it is frequently overestimated. Especially for sulfur dioxide, the actual filtering is slight and can mostly be disregarded. The situation may be different for other gases.

Wind Protection as Protection from Smoke

The reduced wind velocity in forests and forest belts indirectly has a favorable effect. Too high wind velocities are disadvantageous for plants and increase the smoke hazards. Wind protection represents a physiological relief for plants. In numerical terms, this is probably the most important of all four effects taken together. But it does not change gas concentration. Suitable protective measures (protective barriers) are possibly useful and effective at sites which are particularly strongly exposed to wind.

If the term "screening" is used for the action of forest belts or forest stands on waste gases, one must be aware of which single effect is meant by this term; otherwise, it may lead to misunderstandings. It should be noted that the first and second effect move in opposite directions to each other. But the second effect probably predominates in comparison with the first effect in forest belts. In large forest areas, the second effect probably becomes less important. Yet, an exact separation of the individual effects is possible only by means of highly accurate measurements, because both effects are generally very small in quantitative terms.

At first glance, the often quoted findings of Woelfle [5] seem to contradict our statements regarding the influence of wind (effect 1). For his study, a cloud of smoke was produced on the ground in front of the edge of the forest. At first, concentration decreased with increasing altitude. The cloud of smoke moved towards the edge of the forest. Woelfle then found less smoke in the trunk area than above the crown cover and in front of the forest. He explained it by the lifting of the flow caused by the forest. It should be noted that the smoke concentrations produced were not stationary but lasted only for a very short time (about 20 seconds). The upper part of the cloud of smoke could move ahead of the lower portion as a result of the higher wind velocities above the trees. Therefore, relatively low concentrations developed in the trunk area. If the smoke had been produced for an extended period, the trunk area would gradually have formed higher concentrations than the space above the crowns.

The question asked in the title may now be answered. Two prerequisites have to be met if smoke concentration is to be lowered by a forest belt.

First of all, smoke concentration has to decrease as altitude increases. The forest belt has to be at a higher altitude than the original level of distribution of the axis of the plume of smoke. This may be realized, for example, when the immission source is located in a valley, while the forest belt is located on the upper slopes of a mountain, a mountain ridge or a mountain plateau. In the lowland, smoke concentration decreases as altitude increases only when the immission sources are in the immediate vicinity of the ground (possibly in open-pit mines).

Secondly, the forest belt must not be too far away from the smoke immission

source. As distance becomes greater, the change in the distribution of smoke concentration with increasing height becomes lower due to the turbulent whirling of smoke, which is generally present. When distance is great, the altitude profile has been flattened and widened so much that the additional whirling effect caused by the forest belt is hardly of any importance. The effect of the forest belt is all the more clear the closer it is to the immission source.

Both prerequisites are met only in very rare instances. One example of the favorable effects of a forest belt is quoted by Wentzel [6]. From topographical conditions which prevailed in his example, it can be seen that both prerequisites were met. However, it cannot readily be determined which role the fourth effect played in the favorable action.

If both prerequisites are fulfilled, and if a low source of immission is replaced by a higher one (construction of a tall smoke stack) then it is possible that a reversal of the altitude gradients occurs in the distribution of smoke. An increase with altitude may develop from an original decrease with altitude. In such a case, the second effect can no longer have any favorable influence. Of course, the positive consequences which the construction of a tall smoke stack has on the concentration of waste gases on the bottom of a valley, are not affected.

The author is always grateful for examples in which both prerequisites have been met. Of interest here is the smoke damage area along the ridge of the Ore Mountains which lies above the original level of smoke distribution (immission sources of the northwest Bohemian depression). Unfortunately, here the distance

from the source of immission is very great. At any rate, on the basis of special meteorological conditions [2] the possibility is given at times for a great decrease of concentration as the altitude increases. For a more exact examination, it must of course be attempted to conduct actual concentration measurements, especially in order to separate the influences of the second and fourth effects. Due to the fact that variations in concentration are expected to be low, such measurements must be highly accurate, or at least a sufficiently large number of samples must be used.

In a large majority of cases, forest belts can be effective only through the physiological fourth effect and not the first two effects which are purely meteorological. This physiological protection extends only to wind-sensitive plants but not to human beings who are primarily affected by the concentrations of smoke and waste gases. But there is no noticeable reduction of this concentration in general - at least regarding $SO_2$ - as a result of forest belts or forest stands.

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